The behavioral effects of index insurance in fisheries

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Fisheries are vulnerable to environmental shocks that impact stock health and fisher income. Index insurance is a promising financial tool to protect fishers from environmental risk. However, insurance may change fisher's behavior. It is imperative to understand the direction fishers change their behavior before implementing new policies as fisheries are vulernable to overfishing. We provide the first theoretical application of index insurance on fisher's behavior change to predict if index insurance will incentivize higher or lower harvests in unregulated settings. We find that using traditional fishery models with production variability only originating through stock abundance leads fishers to increase harvest with index insurance. However, fishers are adaptable and experience multiple sources of risk. Using a more flexible specification of production shows that index insurance could raise or lower harvest depening on the risk mitigation stragtegies available for fishers and the design of the insurance contract. We demonstrate the magnitude of potential change by simulating from parameters estimated for three Norwegian fisheries. Fisheries with index insurance contracts protecting extraction risks may increase harvest by 10% or decrease by 2% depending on the risk effects of inputs. Insurance contracts protecting stock risk will lead to 6-20% increases in harvest. Before widespread adoption, careful consideration must be given to how index insurance will incentivize or disincentivize overfishing.

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1 Introduction

Fisheries are exposed to numerous environmental risks that impact biological and economic sustainability(Alvarez *et al.* 2006; Lehodey *et al.* 2006; Rogers *et al.* 2019; Cheung *et al.* 2021; Oken *et al.* 2021; Smith *et al.* 2023). There are limited financial tools available to protect fishing communities against environmental risks (Sethi 2010; Kasperski and Holland 2013). Index insurance is a new financial tool that has significant potential to bolster community welfare in response to disastrous weather events (Maltby *et al.* 2023; Watson *et al.* 2023; Hobday *et al.* 2025). However, insurance possesses moral hazards that may induce behavior change in fishers. In this paper, we provide the first examination of whether index insurance will lead to incentives that increase or decrease fishery harvest. We apply our theoretical findings to an empirical setting in three Norwegian fisheries.

Fishers are highly sensitive to risk, especially income risk, and demonstrate risk aversion despite working a seemingly risky profession (Smith and Wilen 2005; Holland 2008; Sethi 2010). Individual choices by fishers and fishery management mitigate environmental risk. Fishers actively avoid fishing in destructive weather at the expense of lost income (Pfeiffer 2020). Individual efforts to mitigate risk include choosing consistent, known fishing grounds over risking exploring unknown spots (Holland 2008) or choosing to fish less after storms and hurricanes (Pfeiffer 2020; Pfeiffer *et al.* 2022). However, these efforts are unlikely to completely eliminate risk. Additional financial tools may be needed to address income risk as a result of environmental fluctuations (Sethi 2010; Kasperski and Holland 2013). There is growing interest in developing new financial tools to alleviate income risk for coastal communities (Wabnitz and Blasiak 2019; Sumaila *et al.* 2020).

Index insurance may be an ideal financial tool for risk management in fisheries as it is scalable, protects against environmental shocks, and smooths income for fishers (Watson *et al.* 2023; Hobday *et al.* 2025). Index insurance uses independent measures of weather as the basis for issuing payouts to all policyholders. For example, a pilot program through the Caribbean Oceans and Aquaculture Sustainability Facility (COAST) pays out a set amount to fishers when indices of wave height, wind speed, and storm surge indicate a hurricane (Sainsbury *et al.* 2019).

One crucial area that remains under studied is the potential influence of insurance on fisher behavior. Moral hazards are decisions by insured agents that they would not otherwise take if they were uninsured (Wu *et al.* 2020). Although practitioners favor index insurance on the belief that it avoids moral hazard (RARE 2021), there are two components to insurance moral hazards: "chasing the trigger" and "risk reduction" that must be considered. "Chasing the trigger" is the directed behavior of policyholders to increase the likelihood of a payout. For example, a fisher might choose to fish less to receive an indemnified harvest insurance payment. Index insurance completely eliminates this moral hazard as the index is independent of fisher choices, e.g. fishers cannot affect sea surface temperature. "Risk reduction" occurs when policyholders possess an insurance contract that protects them from risk, leading them to reoptimize their decisions. Index insurance remains susceptible to this element of moral hazard. One possible response by fishers is to take on additional risk by fishing more. Alternatively, the risk protection offered by insurance could encourage fishers to fish less as insurance payouts sufficiently cover income loss. All preliminary analyses of fisheries index insurance are missing rigorous assessment of risk reduction moral hazards.

In this paper, we assess how index insurance moral hazards could change fisher input choices. Subsequently, the changes in inputs lead to changes in harvest and thus sustainability. Fisheries remain vulnerable to overfishing (FAO 2020). It is imperative to ensure new policies, such as index insurance, do not provide perverse incentives that degrade long term sustainability by encouraging greater fishing pressures.

Previous studies articulated hypothetical examples of moral hazards in potential fishery indemnity insurance programs, such as encouraging fishers to fish in foul weather or to not exit the fishery after a bad year of harvest (Herrmann *et al.* 2004; Watson *et al.* 2023). However, neither study built testable models to uncover risk reduction moral hazard impacts on fisheries.

Research from agriculture provides compelling evidence that behavior change ought to be expected in fisheries. Index insurance applied to grazing in pasture commons shows clear evidence of risk reduction moral hazards leading to environmental degradation (Müller *et al.* 2011; Bulte and Haagsma 2021). Other studies from agriculture find that the impact of insurance on environmental sustainability depends on the underlying risk reducing or increasing qualities of inputs used in production (Ramaswami 1993; Mahul 2001; Mishra *et al.* 2005). Risk increasing (decreasing) inputs will always lead to increased (decreased) input use with insurance. Numerous agricultural studies confirm insurance incentivizes changes in input use (Horowitz and Lichtenberg 1993; Babcock and Hennessy 1996; Smith and Goodwin 1996;

Goodwin *et al.* 2004; Mishra *et al.* 2005; Cai 2016; Deryugina and Konar 2017; Claassen *et al.* 2017; Elabed and Carter 2018; Sibiko and Qaim 2020; Stoeffler *et al.* 2022; Sloggy *et al.* 2025).

Fisheries differ from agriculture in crucial ways, thus motivating an analysis of the behavioral effects of index insurance in this new setting. In a standard fisheries model, production by a fisher depends on the abundance of the resource, as measured by the fish stock. In this case, there is a positive relationship between output and inputs of labor and capital. For example, more fishing boats results in a greater catch for a given fish stock. When the fish stock is subject to stochastic shocks, inputs will be risk-increasing and, thus, index insurance covering biological stock risk will always increase input use and harvest of the resource. This suggests that index insurance will be in conflict with conservation goals in fisheries. However, fishers also face risk that is independent of biological risk. For example, weather and wave conditions may make it difficult to catch fish or new regulations may limit where fishing can take place. Inputs that interact with extraction shocks may be risk-increasing or risk-decreasing. Therefore, index insurance applied to extraction risk has the potential to reduce harvest and conserve fish stocks. A complete analysis of index insurance in fisheries is needed to understand the different types of risk faced by fishers, alternative ways in which insurance contracts can be designed, and whether insurance will be compatible with conservation goals.

To estimate the magnitude of potential harvest changes, we numerically simulate a model from parameter estimations of Norwegian fisheries from Asche *et al.* (2020). The Norwegian fisheries show index insurance could raise harvest by 20% or lower harvest by 2% contingent on the fishery input characteristics and contract type. All contracts specified to protect biological stock risk showed large increases in harvest regardless of the extraction risk effects. Currently, most proposed insurance contracts are examining triggers based on stock risk, such as sea surface temperature or chlorophyll-a (Watson *et al.* 2023). Without additional constraints, these types of contracts will incentivize greater exploitation of vulnerable fish stocks.

The remainder of the paper is structured as follows. Section 2 demonstrates how assuming standard fishery production models will always bias index insurance towards overfishing. We then present a new stochastic production function for fisheries that integrates both stock and extraction risk in Section 3. Fishers now face multiple risks where contracts could be specified to protect either risk. In this new setting, we prove how index insurance will change fisher behavior, and how the outcome depends on the risk effects of inputs as well as the type of insurance contract. Section 4 extends the theoretical model to account for multiple inputs in fishing that reflects the decisions of fishers in the empirical setting. Section 5 numerically estimates potential harvest changes with an index insurance program. Parameters are calibrated with an application to Norwegian fisheries through the results of Asche *et al.* (2020). Section 6 concludes with a discussion on the suitability of fishery index insurance.

2 Index Insurance with standard fishery production

Here we develop a model of fishery production under risk. We are primarily interested in within-season input decisions and risk, so we omit time subscripts, but will be explicit about when random variables are known, or unknown, to fishers. We begin with a canonical model of fishery production.

Fishers choose an input x that interact through an increasing concave production technology $f(x)$[1]. Fish biomass is B, and total production, or "harvest", y is given by:

$$y = Bf(x) \tag{1}$$

We assume that B is unknown prior to the choice of x, but that some information on B is available. Specifically, we assume $B = \hat{B} + \theta$, where $\hat{B}$ is known and θ is mean zero additive error term, with known variance σ_θ^2; we will refer to θ as the "stock risk". This implies that Equation 1 can be rewritten:

$$y = \hat{B}f(x) + \theta f(x) \tag{2}$$

This approach combines a standard model of fishery production (Equation 1) with the simple observation that biomass, which affects harvest, is unknown prior to the choice of inputs. With this model, we can examine how index insurance affects incentives around input choice. Under standard assumptions, fishers are price takers, incur convex costs, and are risk averse over profits.

We can define a simple profit function where prices are set to one in Equation 3

$$\pi = \hat{B}f(x) + \theta f(x) - c(x) \tag{3}$$

We create an insurance lottery through a contract that uses θ as the index. The trigger $\bar{\theta}$ initiates a constant payout γ when the index falls below the trigger, $\theta < \bar{\theta}$.

Actuarially fair insurance implies the premium, ρ, paid in both lottery outcomes to be the probability of receiving a payout times the payout amount, $\rho = J(\bar{\theta})\gamma$, where $J(\theta)$ is the cumulative distribution of the shock. Additionally, if we set the trigger to zero, $\bar{\theta} = 0$, profit will enter corresponding bad and good states when θ is positive and negative respectively.

Fishers are expected utility maximizers. To do so, they need to make decisions on the marginal profitability in the good and bad states. We introduce the following lemma to help us compare marginal profits in both states:

[1]Common specifications of $f(x)$ are Cobb-Douglas or linear harvest from Gordon-Schaefer.

Lemma 2.1. *Index insurance contracts built on θ will always lead to higher expected marginal profits in the good state*

$\frac{\mathbb{E}[\partial\pi|\theta<\bar{\theta}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\theta>\bar{\theta}]}{\partial x} < 0$

The proof of Lemma 2.1 is included in the appendix.

Risk aversion is a necessary condition for insurance to be desirable (Outreville 2014). Therefore, we assume fishers are risk averse to income shocks through a concave utility function. Fishers will maximize their own expected utility in the lottery by choosing the input given an exogenous insurance contract (Equation 4).

$$\begin{aligned} U \equiv \max_x \mathbb{E}[U] = &\int_{-\infty}^{\bar{\theta}} j(\theta)u(\pi(x,\hat{B},\theta) + (1-J(\bar{\theta}))\gamma)d\theta \\ &+ \int_{\bar{\theta}}^{\infty} j(\theta)u(\pi(x,\hat{B},\theta) - J(\bar{\theta})\gamma)d\theta \end{aligned} \tag{4}$$

The first order condition that solves Equation 4 is then:

$$\begin{aligned} \frac{\partial U}{\partial x} &= \int_{-\infty}^{\bar{\theta}} j(\theta)u_x(\pi(x,\hat{B},\theta) + (1-J(\bar{\theta}))\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta)d\theta \\ &+ \int_{\bar{\theta}}^{\infty} j(\theta)u_x(\pi(x,\hat{B},\theta) - J(\bar{\theta})\gamma)\frac{\partial \pi}{\partial x}(x,\hat{B},\theta)d\theta \\ &= 0 \end{aligned} \tag{5}$$

To find the effect of insurance on optimal input, we use the implicit function theorem to examine how input choice varies with the insurance payout γ:

$$\frac{\partial x^*}{\partial \gamma} = -\frac{\frac{\partial U}{\partial x \partial \gamma}}{\frac{\partial^2 U}{\partial x^2}} \tag{6}$$

We use γ to test insurance effects, because a marginal change in the payout increases the value of insurance[2]. Receiving more compensation in the bad states provides greater boosts to utility for risk averse fishers. We define a feasible contract to be levels of γ that improve expected utility relative to no insurance.

By the sufficient condition of a maximization problem, $\frac{\partial^2 U}{\partial x^2}$ is negative so we can focus solely on the numerator to sign the effect. The numerator of Equation 6 is given by:

[2]As shown in Section 5, marginal utility reaches a maximum value before decreasing at high γ. Therefore we assume the change in γ occurs in regions of increasing marginal utility in γ.

$$
\begin{aligned}
\frac{\partial U}{\partial x \partial \gamma} = &\int_{-\infty}^{\bar{\theta}} j(\theta) u''(\pi(x, \hat{B}, \theta) + (1 - J(\bar{\theta}))\gamma) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta)(1 - J(\bar{\theta})) d\theta \\
&+ \int_{\bar{\theta}}^{\infty} j(\theta) u''(\pi(x, \hat{B}, \theta) - J(\bar{\theta})\gamma) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta)(-J(\bar{\theta})) d\theta
\end{aligned} \tag{7}
$$

Proposition 2.1. *For feasible insurance contracts specified at trigger $\bar{\theta} = 0$ with production function $y = \hat{B} f(x) + \theta f(x)$, optimal harvest will always increase with an increase in γ.*

Proof. Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 7. For brevity, all like terms including γ are indicated by $u(\cdot)$.

$$
\begin{aligned}
\frac{U}{\partial x \partial \gamma} = &J(\bar{\theta})(1 - J(\bar{\theta})) u''(\cdot) \\
&\times \left[\int_{-\infty}^{\bar{\theta}} j(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta) d\theta - \int_{\bar{\theta}}^{\infty} j(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta) d\theta \right]
\end{aligned} \tag{8}
$$

The first term of Equation 8 is negative by the concavity of utility, $u''(\cdot) < 0$. The second term of Equation 8 is negative by Lemma 2.1.

Therefore, an index insurance contract built assuming a standard fishery production model will always lead to increased input use, and thus more harvest. □

Proposition 2.1 immediately challenges the sustainability of index insurance in fisheries. Fishers will always increase input choices if we assume a standard fishery production model. The intuition why fishers would increase harvest is identicial to observations from agriculture that studied similar specifications of production [3] (Ramaswami 1993; Mahul 2001). Risk increasing inputs increase the variance of harvest (Just and Pope 1978). Effort is inherently "risk-increasing" in Equation 2 and leads to more variance[4]. Insurance lowers exposure to income variance. With less marginal exposure to risk, fishers can increase their risky input use.

However, fishers are exposed to more margins of risk and possess means to mitigate those risks beyond ways captured in the simple canonical model. In the next section we expand fishery production to include multiple sources of risk, and incoporate risk mitigation strategies present in fisheries.

[3] Equation 2 is a special case of the production function used in Mahul (2001) where $f(x)$ is exactly equal to $h(x)$ used in his specification.

[4] Note that: $V(y) = \sigma^2 f(x)^2$, the derivative is always positive because $\frac{f(x)}{\partial x} > 0$: $\frac{\partial V(y)}{\partial x} = 2\sigma^2 \frac{\partial f(x)}{\partial x}$

3 Index insurance with risky fishery production

Anecdotally and empirically, fishers make informed decisions to mitigate risk beyond just exposure to stock risk (Kirkley and Strand 1998; Eggert and Tveteras 2004; Kompas *et al.* 2004; Smith and Wilen 2005; Holland 2008; Sethi 2010; Pfeiffer 2020; Pfeiffer *et al.* 2022). Stock risk, θ, remains an inevitable source of risk that we must maintain in any fishery model, but we expand the standard fishery model in Equation 2 to Equation 9 by adding a second source of risk called extraction risk, ω, and new ways inputs could interact with extraction risk through $h(x)$.

$$y = f(x)\hat{B} + \theta f(x) + \omega h(x) \tag{9}$$

All other forms of risk not captured by stock risk are extraction risk, ω, where ω is a random variable with $\mathbb{E}[\omega] = 0$ and variance σ_ω^2. Foul weather, regulatory changes, or inherent variability in extraction all impact fisher production. Fisher inputs may interact with these risks through the extraction risk effect function $h(x)$. Extraction risk effects may reduce or increase risk. Inputs that increase variance are called risk increasing, $h_x(x) > 0$, and inputs that decrease variance are called risk decreasing, $h_x(x) < 0$ (Just and Pope 1978).

We will refer to production in the form of Equation 9 as "risky production". Risky production is more flexible than the standard fishery production model in Equation 2 as it allows for two sources of risk and multiple avenues for fishers to mitigate risk. Risky production nests the standard fishery production model as a special case when $\omega = 0$ or $h(x) = 0$. It also maintains increasing mean production in inputs so that changes in inputs correspond to changes in expected harvest and conservation.

With two sources of risk and adaptive margins, we have created a more nuanced representation of risky production in fisheries. However, it is not immediately clear how index insurance will affect fisher harvest decisions with Equation 9. We can ammend the insurance framework from Section 2 to assess the potential behavior implications of an insurance contract to protect against stock, θ, or extraction risk, ω.

Profits with risky production update Equation 3 to Equation 10:

$$\pi = f(x)\hat{B} + \theta f(x) + \omega h(x) - c(x) \tag{10}$$

We assume fishers and insurance companies have perfect information on both distributions of random variables.

We create insurance lotteries through contracts that use either ω or θ as the trigger. For notational ease, we present the model with a contract built on ω, but the structure is interchangeable with contracts built on θ. By allowing contracts on only one of the random variables, we introduce basis risk as a contract triggered solely on ω cannot protect against all the biological risk of θ. We assume that θ and ω are independent[5]. An example of how shocks could be independent is that stock shocks operate at different time scales than extraction shocks (Alvarez *et al.* 2006).

Payouts remain a constant γ and fishers pay a premium, $\rho = J(\bar{(}\omega)\gamma)$, in both states.

As before, the maginal profits in both states are crucial to understanding fisher behavior. For contracts built on ω the risk effects function $h(x)$ becomes influential. We introduce the following lemma to help us compare marginal profits in both states:

Lemma 3.1. *Expected marginal profit is higher in bad states for risk decreasing inputs when insurance contracts are built on extraction risk ω.*

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x} > 0$ *if* $h_x(x) < 0$.

Otherwise, risk increasing inputs lead to higher expected marginal profit in the good states.

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x} < 0$ *if* $h_x(x) > 0$

The proof of Lemma 3.1 is included in the appendix. The results of Lemma 2.1 hold even with risky production in Equation 9 as shown in the proof of Lemma 2.1.

Fishers consider the joint distribution $j(\omega,\theta)$ of shocks to maximize their utility with exogenous insurance contracts.

$$\begin{aligned} U \equiv \max_x \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[&\int_{-\infty}^{\bar{\omega}} j(\omega,\theta) u(\pi(x,\hat{B},\theta,\omega) + (1 - J(\bar{\omega}))\gamma) d\omega \\ &+ \int_{\bar{\omega}}^{\infty} j(\omega,\theta) u(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) d\omega \Bigg] d\theta \end{aligned} \tag{11}$$

The first order condition that solves Equation 4 is then:

$$\begin{aligned} \frac{\partial U}{\partial x} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta) u_x(\pi(x,\hat{B},\theta,\omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega \\ &+ \int_{\bar{\omega}}^{\infty} j(\omega,\theta) u_x(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega \Bigg] d\theta \\ &= 0 \end{aligned} \tag{12}$$

Changes in optimal input due to insurance remain characterized by the implicit function theorem of Equation 6. Now the numerator is given by:

[5] In the appendix we include proofs when shocks are perfectly correlated, but the results become difficult to extract clear insights

$$
\begin{aligned}
\frac{\partial U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{\omega}} j(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega \\
& + \int_{\bar{\omega}}^{\infty} j(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega \Bigg] d\theta
\end{aligned}
\tag{13}
$$

We examine input decisions with insurance contingent on the source of risk the insurance is designed to protect. Proposition 3.1 demonstrates that contracts built on extraction risks depend on the underlying input risk effects.

Proposition 3.1. *For feasible index insurance contracts specified at trigger $\bar{\omega} = 0$, optimal fisher harvest will decrease with an increase in γ when $h_x(x) < 0$ and increase when $h_x(x) > 0$.*

Proof. Independence of ω and θ allows us to factor out the joint distribution in the integral of Equation 13 into the respective marginal distributions shown by $j_\theta(\theta)$ and $j_\omega(\omega)$ respectively.

$$
\begin{aligned}
\frac{U}{\partial x \partial \gamma} = \int_{-\infty}^{\infty} j_\theta(\theta) \Bigg[& \int_{-\infty}^{\bar{\omega}} j_\omega(\omega) u''(\pi(x,\hat{B},\theta,\omega) + (1-J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1-J(\bar{\omega})) d\omega \\
& + \int_{\bar{\omega}}^{\infty} j_\omega(\omega) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega \Bigg] d\theta
\end{aligned}
\tag{14}
$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 14. For brevity, all like terms including γ are indicated by $u(\cdot)$.

$$
\begin{aligned}
\frac{U}{\partial x \partial \gamma} = & \int_{-\infty}^{\infty} j_\theta(\theta) J(\bar{\omega})(1-J(\bar{\omega})) u''(\theta,\cdot) \\
& \times \left[\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega - \int_{\bar{\omega}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega \right] d\theta
\end{aligned}
\tag{15}
$$

The first term outside the brackets is negative by the definition of concave utility, $u'' < 0$. Lemma 3.1 demonstrates the interior of the brackets is positive when $h_x(x) < 0$ as the marginal profit in the bad state is greater than the marginal profit in the good. Therefore, index insurance will decrease input use for risk decreasing inputs when the extraction shocks are independent of stock shocks.

When $h_x(x) > 0$, the interior sign of the brackets in Equation 15 is negative by Lemma 3.1. Therefore, index insurance will increase input use for risk increasing inputs.

Direction of input change will exactly match the direction of harvest change by the properties of the production function. □

Proposition 3.1 shows contracts specified on extraction risk could have positive or negative effects on harvest depending on the risk effects of the input. Insurance lowers the use of risk decreasing inputs because the need to protect against risk with that input is replaced by the risk mitigating qualities of insurance. Insurance increases risk increasing inputs as it protects against additional risk allowing fishers to expand production without taking on greater risk. The stock risk persists when contracts are specified on extraction risks, but is not influential in the marginal decision with insurance. Instead, if we specify a contract on the stock shocks, then the stock risk effects become more prevalent and distinctly changes the harvest outcome.

Proposition 3.2. *For feasible index insurance contracts specified at trigger $\bar{\theta} = 0$, optimal harvest will always increase with an increase in γ.*

Proof. A contract built with θ will follow the same steps as the proof for Proposition 3.1 with the only difference being in the integral bounds and the differential variables as shown in Equation 16. The 2nd term of Equation 16 is always negative by Lemma 2.1. Therefore, a contract built on θ will always increase optimal input use.

$$\begin{aligned} \frac{U}{\partial x \partial \gamma} = &\int_{-\infty}^{\infty} j_{\omega}(\omega) J(\bar{\theta})(1 - J(\bar{\theta})) u''(\omega, \cdot) \\ &\times \left[\int_{-\infty}^{\bar{\theta}} j_{\theta}(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta - \int_{\bar{\theta}}^{\infty} j_{\theta}(\theta) \frac{\partial \pi}{\partial x}(x, \hat{B}, \theta, \omega) d\theta \right] d\omega \end{aligned} \tag{16}$$

The change in input use will lead to higher expected optimal harvest. □

Proposition 3.2 demonstrates a clear bias towards overfishing with contracts solely specified on θ. Increased stock abundance directly leads to higher variance. Insurance only protects against the additional stock risk, and encourages fishers to expand production. Fishers have no means to lower stock risk through input choices. The marginal change in variance from insurance cannot be influenced by extraction risks due to the additive specification.

Insurance contracts can only influence fisher input choices if the inputs interact with the source of risk the contract is designed to protect. Choosing which risk to protect has important consequences for moral hazard effects.

4 Insurance with multiple inputs

The single input model provides clear, testable insights. However, real world fisheries are more complex than single input models. We develop a multi-input model to represent this complexity. The multi-input model provides the foundation of our numerical analysis that leverages parameter estimations from Asche *et al.* (2020). Their study estimated production and risk effect parameters across three inputs in Norwegian fisheries. The numerical analysis will allow us to quantify the directional effects of insurance on fisher behavior for valuable Norwegian fisheries.

We extend the model of the previous section to two inputs, $X \in \{x_a, x_b\}$. Two inputs sufficiently articulate the complexities that arise while still remaining tractable to solve.

There are two additional effects to consider when adding more inputs. The interaction between inputs leads to the first effect. Changes in input use may not correspond to the direction dictated by their respective extraction risk effects. For example, a fisher may not choose to reduce a risk decreasing input if the cross partial effects of production and risk negatively impact production of another input. We summarize the conditions that lead to unequivocal changes in input use in Proposition 4.1.

Proposition 4.1. *In fisheries with two inputs, index insurance specified with contracts on ω will increase (decrease) the optimal use of a specific input if the input's risk effects are increasing (decreasing) when the following sufficient condition is true:*

$\frac{\partial U}{\partial x_a \partial x_b} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial U}{\partial x_a \partial x_b} < 0$ *when inputs have opposite risk effects.*

Otherwise, index insurance may lead to ambiguous changes in the input regardless of the input's own risk effect.

The proof is included in Section A.3.

The second effect is a straightforward consequence of adding inputs. While insurance may incentivize greater use of one input, it may simultaneously reduce use of another. The net change in harvest depends on both the magnitude of adjustment in each input and their relative production elasticities.

Proposition 4.2. *When index insurance leads to increases (decreases) of both inputs, total expected harvest will increase (decrease).*

Otherwise, total change in expected harvest depends on the relative change in input use and $\frac{\partial f(x_m)}{\partial x_m}$

Proof. The total derivative of expected harvest is:

$$\frac{d\mathbb{E}[y]}{dx} = \hat{B}\frac{\partial f(x_a, x_b)}{\partial x_a}dx_a + \hat{B}\frac{\partial f(x_a, x_b)}{\partial x_b}dx_b \tag{17}$$

Marginal production is positive, therefore $\frac{\partial f(x_m)}{\partial x_m} > 0$ for either input represented by x_m. When $dx_a > 0$ and $dx_b > 0$, Equation 17 is always positive. The opposite is true when $dx_a < 0$ and $dx_b < 0$.

For inputs with changes in opposite directions, Equation 17 is positive or negative contingent on the relative weight between $\frac{\partial f(x_a,x_b)}{\partial x_a}dx_a$ and $\frac{\partial f(x_a,x_b)}{\partial x_b}dx_b$ □

Proposition 4.2 shows that reductions in certain inputs may be offset by subsequent increases in more productive ones, thereby limiting the conservation potential of index insurance. In other words, lowering one margin of production through insurance does not necessarily result in a smaller total harvest.

These two insights will help explain the modeled responses of fishers in Section 5. In general, stock and extraction risk effects remain the leading influences on guiding fishers input choices after buying insurance. Proposition 4.2 and Proposition 4.1 identify that within the complicated nexus of multiple input interactions, certain inputs may dominate the overall outcomes. Both propositions indicate that inputs that share risk effects (e.g. all inputs are risk increasing), ought to have the same conclusions as observed in Section 3. Fisheries that use inputs with opposite risk effects are impossible to sign without further information. We turn to simulations in the following section to elucidate the ambiguity.

5 Numerical Simulations

We use numerical simulation to determine the magnitude of change in input use. First, we analyze reasonable parameter estimates to isolate the magnitude of single input changes. Next, we calibrate the model to estimates from Norwegian fisheries using three inputs from the parameters found in Asche *et al.* (2020). Monte Carlo simulations find expected utility across 1000 random draws of stock and extraction shocks. A comprehensive set of parameters test the sensitivity of fisher input choices with index insurance. All simulations are conducted in R with accompanying code available at nggrimes@github.com/ibi-behavior.

5.1 Simulations with one input

We use the structural form where $f(x) = x^\alpha$ and $h(x) = x^\beta$ to most easily integrate risk increasing or decreasing effects in $h(x)$. Under these functional forms, Equation 10 becomes:

$$\pi = x^\alpha(\hat{\beta} + \theta) + \omega x^\beta - cx^2 \tag{18}$$

Mean production $f(x)$ is concave so that $\alpha > 0$. Extraction risk effects on the input can either be risk increasing or decreasing with $\beta \lesseqgtr 0$. We apply convex costs, $c(x) = cx^2$, for smoother convergence in the maximization procedure. Stock and extraction shocks are normally distributed with $\theta \sim N(0, \sigma_\theta)$ and $\omega \sim N(0, \sigma_\omega)$.

Fishers will choose inputs x to maximize expected utility with an exogenous insurance contract. Constant Absolute Risk Aversion (CARA) utility is used to account for negative shocks and profit loss. Under this contract specification, the maximization problem becomes Equation 19:

$$\begin{aligned} U \equiv \max_x \mathbb{E}[u] &= \mathbb{E}[(1 - \exp(-a(\pi(x, \hat{\beta}, \theta, \omega) + \mathbb{I}(\gamma))] \\ \mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases} \end{aligned} \tag{19}$$

We convert γ to be a percentage of mean optimal profit without insurance for interpretability. For example, $\gamma = 1$ would represent a payout equivalent to expected profit before insurance, and $\gamma = 0$ represents no insurance. Equation 19 shows the insurance payoff function $I(\gamma)$ built on extraction risk with $\bar{\omega}$ as the trigger. A contract built on stock risk would instead use $\bar{\theta}$ and θ as the conditions in the payoff function.

We create a large parameter space to assess the sensitivity of optimal input choices to different model parameters. We vary the relative productivity of the input $\alpha \in \{0.25, 0.5, 0.75\}$, the extraction risk effect of the input $\beta \in \{-0.7, -0.5, -0.3, -0.1, 0.1, 0.3, 0.5, 0.7\}$, the risk aversion parameter $a \in \{1, 2, 3\}$, the stock shock variance $\sigma_\theta \in \{0.1, 0.2, 0.3, 0.4\}$, and the extraction shock variance $\sigma_\omega \in \{0.1, 0.2, 0.3, 0.4\}$.

First, we iterate γ from 0 to 1.5 to show the change in optimal input use for a single input. Selected parameters for Figure 1 are for demonstration purposes. The full parameter space is explored in the accompanying code.

Optimal input use changes monotonically with index insurance for both risk increasing and decreasing inputs (Figure 1). Fishers use more risk increasing inputs for both contract specifications. For risk decreasing inputs, fishers will only use less inputs if the contract is specified on extraction risk. Otherwise, fishers will use more risk decreasing inputs if the contract is triggered on stock risk as shown in the bottom right panel of Figure 1.

The concavity of utility, as demonstrated by the blue parabolas in all panels of Figure 1, implies there exists an optimal amount of insurance for fishers to buy. The monotonicity of input use in all cases suggests that the insurance level that maximizes utility will preserve the sign of input changes. Therefore, an endogenous choice of insurance will not affect the direction of input change, but it will affect the magnitude.

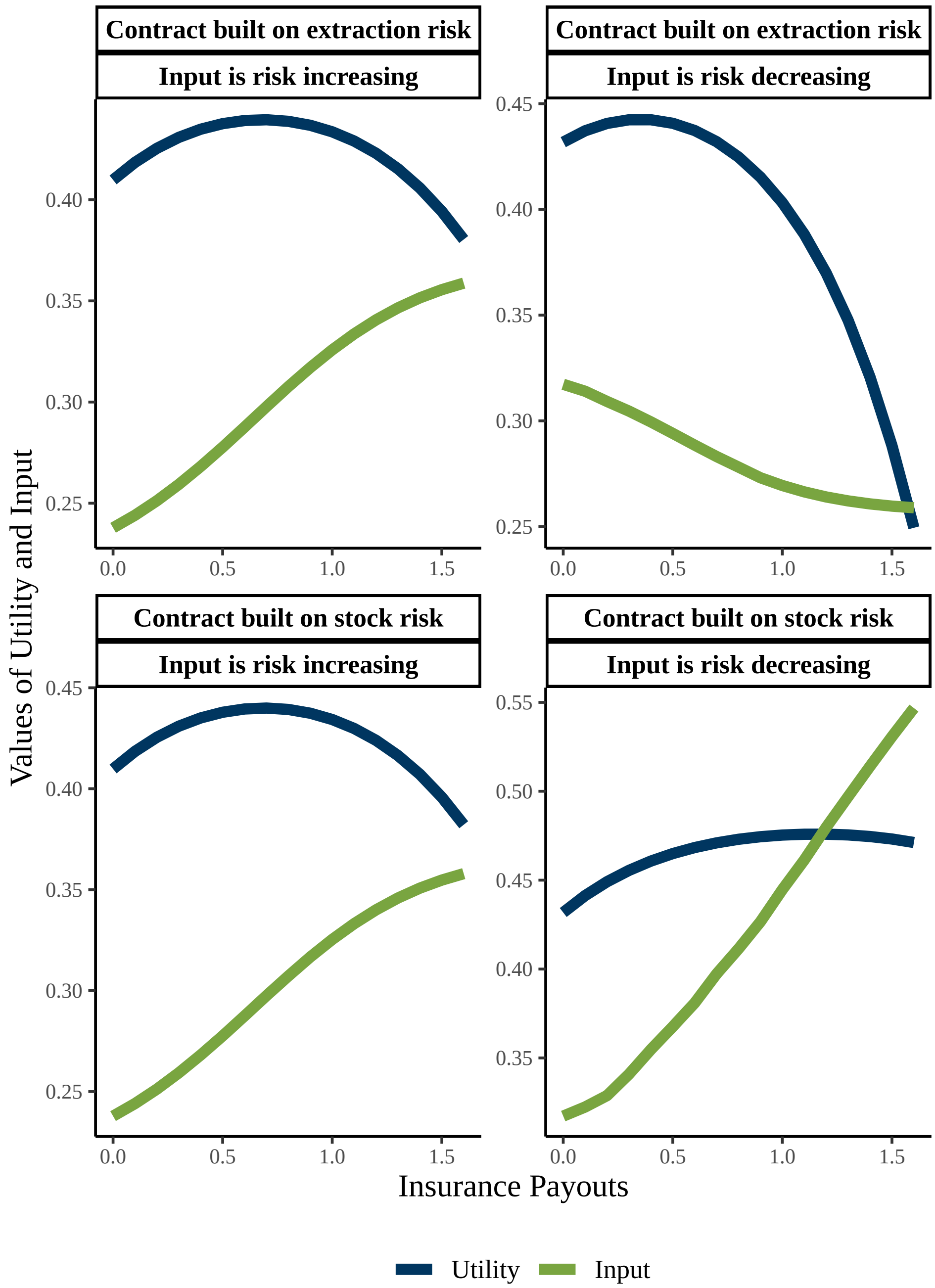

Figure 1: Utility (blue lines) and optimal input use (green lines) with index insurance. Shocks are uncorrelated with high mean productivity ($\alpha = 0.75$), high risk aversion $a = 3$, and relatively high variance in both shocks ($\sigma_w = 0.4$ and $\sigma_t = 0.4$)

For example, contracts protecting against stock risks have peak parabolas further right than contracts on extraction risks in Figure 1. Fishers would be better off with higher levels of insurance coverage. Allowing fishers to choose insurance coverage ensures that the choice of insurance and input use changes are welfare improving and will not bias input choices with over or under investment of insurance. Simulations moving forward will allow fishers to choose both inputs and insurance coverage.

With two choice variables,γ and x, Equation 19 becomes Equation 20:

$$
\begin{aligned}
U \equiv \max_{x,\gamma} \mathbb{E}[u] &= \mathbb{E}[(1 - \exp(-a(\pi(x, \widehat{\beta}, \theta, \omega) + \mathbb{I}(\gamma))] \\
\mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\gamma & \text{if } \omega < \bar{\omega} \end{cases}
\end{aligned}
\tag{20}
$$

Furthermore, we run two groups of simulations: (i) one where the insurance contract indemnifies on ω, as in Equation 19; and (ii) one where the index is constructed on θ, to present results for both Proposition 3.1 and Proposition 3.2.

Contract specification and risk effects control the direction of input change in fisheries. Insurance contracts that protect against extraction risks lead to increases or decreases in optimal input use contingent on the underlying risk effects of the input. All optimal choices of risk decreasing inputs, shown as red bars in Figure 2, decreased if the contract was specified on extraction risks.

The productivity of inputs strongly influences the magnitude of change in input use particularly for risk decreasing inputs. When inputs are relatively less productive (left panel, $\alpha = 0.25$), fishers are more willing to reduce the unproductive input in favor of the protection offered by insurance. They lose less in production while gaining more variance reduction by substituting with insurance. Therefore an important tradeoff exists for risk reducing inputs that does not exist for risk increasing inputs. Fishers demonstrate smaller absolute changes in input use for risk decreasing inputs than risk increasing particularly at higher mean productivity levels in Figure 2. Risk increasing inputs exert stronger effects towards overfishing than risk decreasing inputs have towards conservation.

Contracts built on θ as the index always lead towards overfishing because of the inherent risk increasing characteristics of $f(x)$ (Figure 3). Inputs that are more productive and more risky with higher levels of α will be used more. The right most panel of Figure 3 shows the highest effect where input changes could reach 18%. Extraction risk in $h(x)$ has little influence on changes in optimal input use when the contract is specified on stock risk. Across all levels of the risk effect, β, the magnitude of change remains relatively constant for a given productivity level.

Magnitude of input changes are sensitive to other parameters beyond just mean production elasticity (α). We quickly demonstrate some comparative statics of other important variables such as risk aversion (Panel A in Figure 4), trigger thresholds (Panel B), variance of the

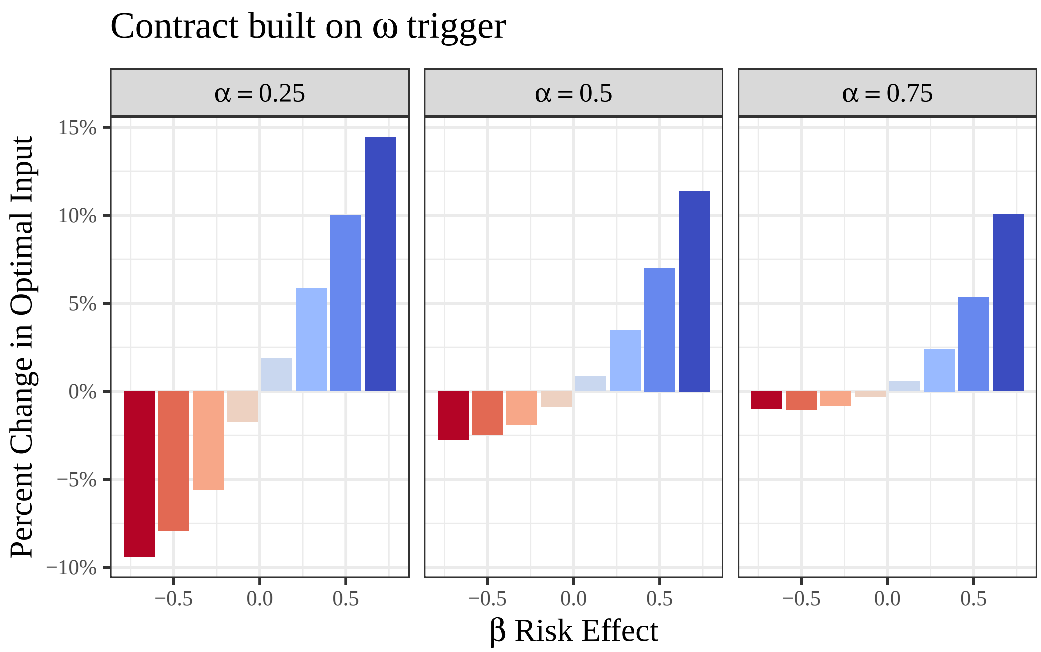

Figure 2: Percentage change in optimal input with an index insurance contract using extraction risk, ω, as the index. Risk increasing inputs (blue bars) always increase input use, while risk decreasing inputs (red bars) always decrease input use. Each panel indicates the mean productivity (α) of the input.

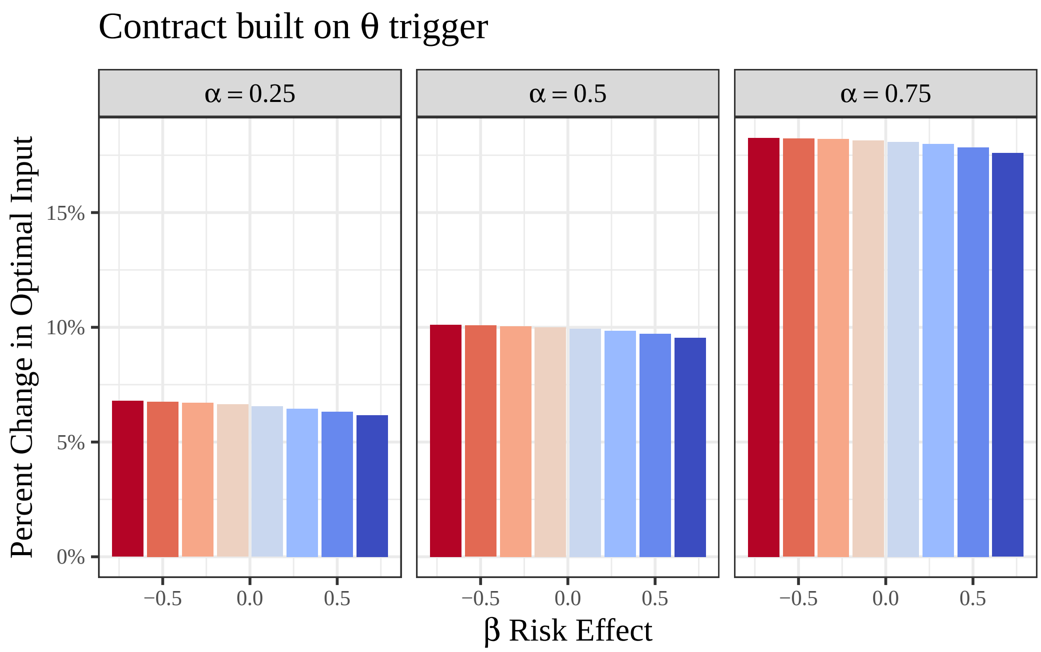

Figure 3: Percentage change in optimal input with an index insurance contract using stock risk, θ, as the index. Risk increasing inputs (blue bars) and risk decreasing inputs (red bars) always increase input use. Each panel indicates the mean productivity (α) of the input.

extraction risk σ_ω (Panel C), and variance of the stock risk σ_θ (Panel D). In each panel, we show the results for the contracts specified on stock risk (θ) and extraction risk (ω). The x-axis of each panel is the extraction risk effect coefficient β, while the y-axis is the percent change in input use with index insurance compared to no insurance. Different colors represent the comparative statics of each new parameter. Across all panels, the new parameters affect only the magnitude of change. The direction of change continues to be determined by risk effects and contract specification.

More risk averse fishers respond more aggressively to insurance (Panel A in Figure 4). Risk aversion implies more sensitivity towards risk. The protection from insurance has greater marginal value for more risk averse fishers. Therefore, they adjust their input use more significantly to take advantage of the risk mitigating qualities of insurance.

Different triggers also lead to different magnitudes of input change, but do not affect the sign changes. While necessary for applying Lemma 3.1 and Lemma 2.1 in the proofs, the results of Proposition 3.1 and Proposition 3.2 would appear to hold if $\bar{\omega} \neq 0$ and $\bar{\theta} \neq 0$. Higher trigger levels protect against extreme or catastrophic shocks. However, those shocks occur much less frequently than those closer to the mean. Fishers are less incentivized to change their expected production levels in the event of rare events. Offering different insurance contracts does change the optimal choice of insurance in line with the results of Lichtenberg and Iglesias (2022).

Fisher input choice is much more responsive to insurance protection from more variable shocks (Panel C and D Figure 4), but it depends on the insurance contract. Similar to risk aversion, the greater the shocks the greater the marginal value of insurance to mitigate those shocks. In more volatile environments, insurance provides significantly more income smoothing leading to similar incentives as the higher risk aversion example. Shocks the insurance does not protect against has little influence on fisher input decisions. If the insurance is designed to protect against one specific shock, it is unsurprising changes in the other independent shock does not affect fishers decisions.

5.2 Application to Norwegian Fisheries

Fishery extraction risk effects are rarely estimated, though appear crucial to determining the magnitude of input change with index insurance. The only study to date that calculates risk effects is that of Asche *et al.* (2020). They used a non-linear estimator to calculate the production and risk parameters of a Just-Pope function across four different vessel types. We will use their coefficient calculations to calibrate an estimate of the magnitude of input and harvest change that index insurance would incentivize if offered to Norwegian fisheries.

Asche *et al.* (2020) aggregated by vessel type and not species, so there is no reasonable estimate for biomass. They accounted for biomass using fixed effects in their regression, but without additional information we cannot parameterize the mean and variance of biomass. Therefore, our simulations normalize mean biomass to 1 and we assume the stock shocks, θ, have a normal distribution and test different levels of variance. Norwegian fisheries are well managed so the

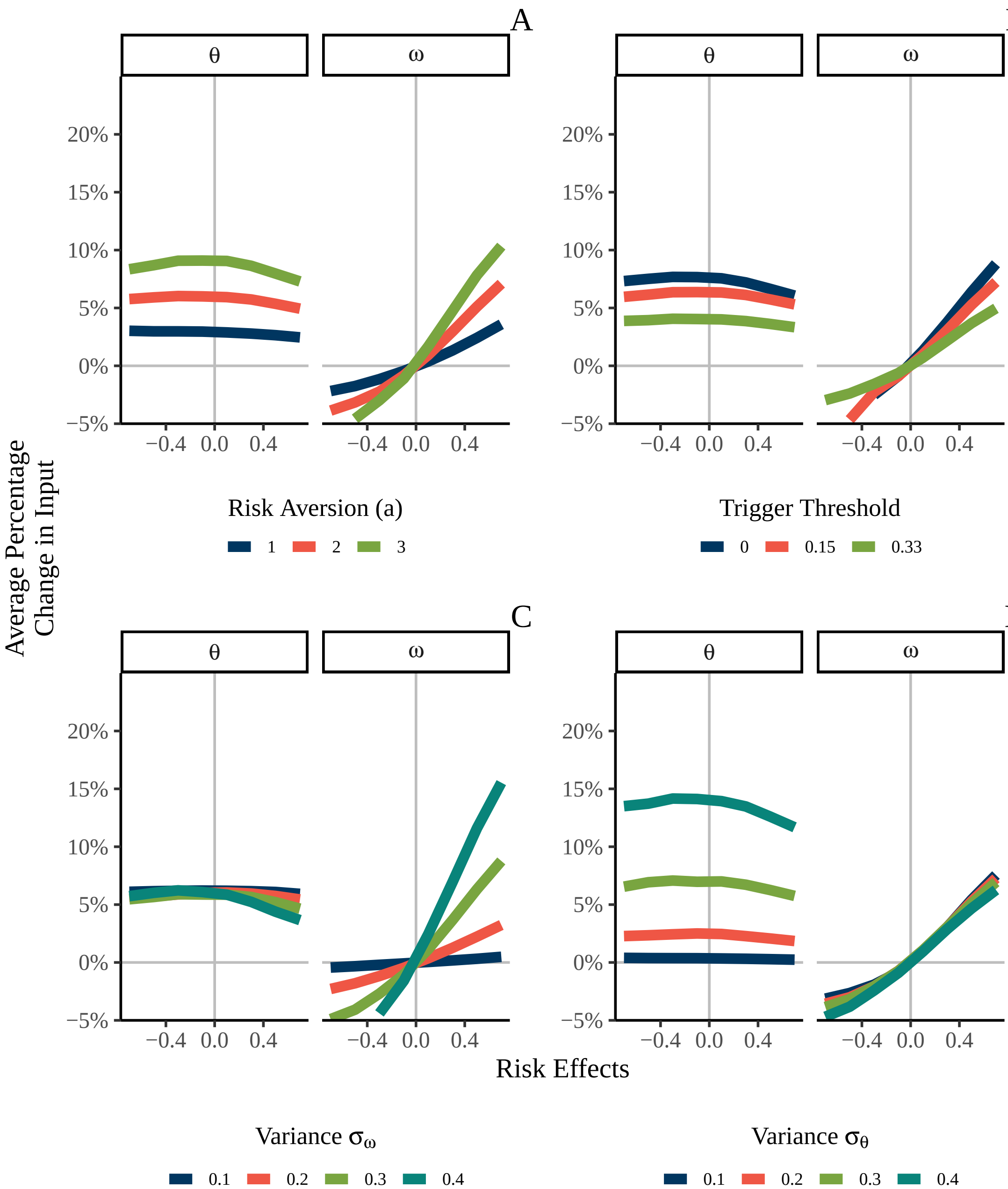

Figure 4: Risk Aversion (A), trigger threshold (B), stock variance σ_ω (C), and extraction variance σ_θ (D) all influence the magnitude of change in input use. Mean production elasticity is set to 0.5. Average percent change in input (y-axis) is summarized across all other parameter combinations for each risk effect value of β. Contracts built on extraction risk are in the subpanels with ω, while contracts built on stock risk are indicated by the θ subpanel.

stock variance could be mitigated through quota systems or accurate stock assessments. The simulation model uses three inputs: capital k, labor l, and fuel f, yielding the following profit in Equation 21:

$$\pi(k,l,f) = k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} (\hat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 \tag{21}$$

Mean production, α, and risk, β, elasticities control the stock and extraction risk effects respectively. Each parameter is indexed to a particular input through the subscript, e.g. fuel mean production elasticity is α_f. Fishers in the simulation choose inputs and insurance coverage to maximize expected utility. We show their choice based on a ω contract (Equation 22), but also run a model specification with a contract built on θ.

$$\begin{aligned}
U &\equiv \max_{\gamma,k,l,f} \mathbb{E}[u] = \mathbb{E}[u(k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} (\hat{\beta} + \theta) + \omega k^{\beta_k} l^{\beta_l} k^{\beta_f} - c_k k^2 - c_l l^2 - c_f f^2 + \mathbb{I}(\gamma)] \\
\mathbb{I}(\gamma) &= \begin{cases} -\rho\gamma & \text{if } \omega \geq \bar{\omega} \\ (1-\rho)\omega & \text{if } \omega < \bar{\omega} \end{cases}
\end{aligned} \tag{22}$$

Table 1 shows the production and risk elasticities of the three vessel types found in Norway[6].

Table 1: Production and Risk elasticities of Norwegian Fisheries from Asche et al., (2020)

	α_k	α_l	α_f	β_k	β_l	β_f
Coastal Seiners	0.294	0.421	0.457	0.184	-0.432	0.119
Coastal Groundfish	0.463	0.421	0.355	0.965	-0.080	0.113
Groundfish Trawlers	0.210	0.106	0.531	-2.788	-0.110	-0.024

We use the same parameter space as the previous simulations to test the sensitivity of fisher input choices with index insurance. We plot the distribution of input change after insurance for all combination of parameters in Figure 5 based on a contract with ω as the index. Figure 5 also allow us to examine whether the conditions of Proposition 4.1 hold with real world combinations. We report the median change as an indicator of the general direction of input change.

Most changes in inputs tend to change in the direction expected of their own individual risk effects. For example, fuel and capital are risk increasing inputs for Coastal Seiners and saw small, but positive increases. Labor was risk decreasing and saw a decline in use. This

[6] In Asche *et al.* (2020), they also estimate a fourth vessel type, purse seiners. However the point estimate for mean production elasticity for labor was negative which violates our assumption of increasing $f(x)$. Therefore we drop purse seiners from our analysis.

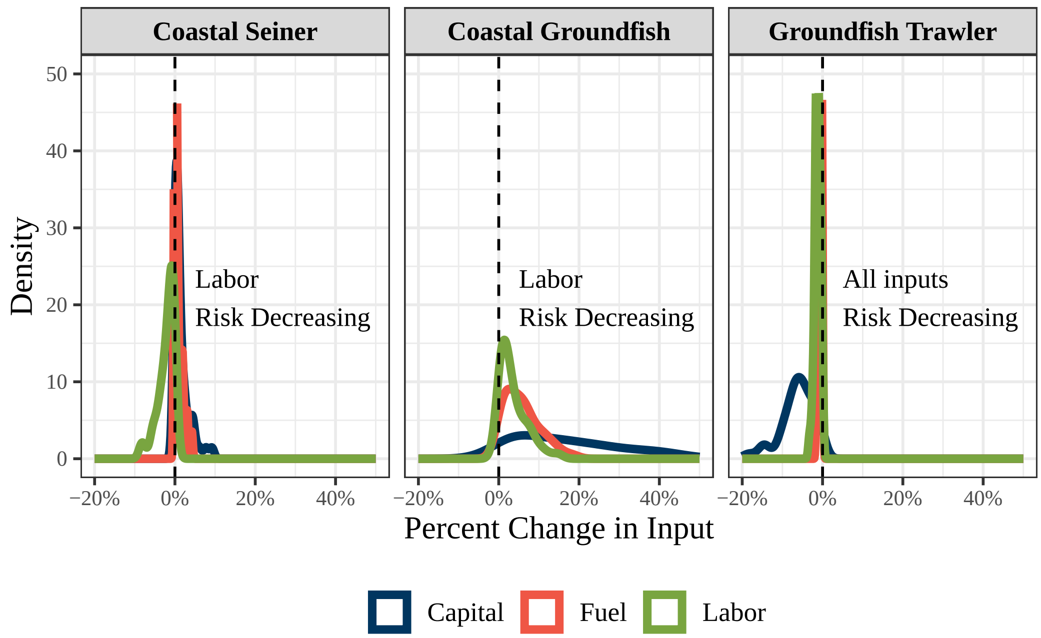

Figure 5: Density plots of the percent change in input use for each vessel type in Norwegian fisheries with contracts built on extraction risk ω. The dashed black line represents no change in input use. Risk decreasing inputs are labeled.

indicates that the conditions of Proposition 4.1 can hold. The relatively even balance between the marginal productivity elasticities and risk elasticities perhaps determine the conditions.

Labor in the Coastal Groundfish fishery is risk decreasing, yet always saw an increase in the simulations. The risk parameter of labor is relatively small compared to the risk increasing coefficients of capital and fuel. The cross partial mix of the inputs may explain why fishers add more labor. As insurance strongly incentivizes capital and fuel increases, labor must also increase to further enhance those other inputs. Here, the conditions of Proposition 4.1 do not hold.

Every input in the groundfish trawler fishery was risk decreasing. With contracts on extraction risks all inputs saw a decline. The largest decline was in capital, because capital possesses the strongest risk decreasing effect out of all inputs.

Recreating the same analysis with contracts on stock risks shows the propensity for stock risk contracts to stimulate increased input use regardless of risk effects (Figure 6). All inputs saw similar increases in each fishery with the exception of capital in the groundfish trawlers. While capital still increased, it did so at a much smaller rate. Capital in the groundfish trawler fishery is the most risk decreasing input out of all the fisheries. Fishers do not need to expand capital production in this case because it already reduces so much risk. Adding insurance marginally reduces some risk, hence the increase, but is not needed as much compared to other fisheries with weaker risk reducing inputs.

Input changes lead to harvest changes. We examine the total change in harvest for all parameters in Figure 7 for a contract triggered on ω. Overall, insurance leads to relatively small changes in harvest for all fisheries, but increases are stronger than decreases. Coastal Groundfish see the largest and most consistent increase in harvest. Median harvest increased by 10% with a max increase of 36%. Coastal Groundfish have the most risk increasing inputs out of the estimated fisheries, and had greater input use (Figure 5).

Coastal Seiners had a relatively balanced spectrum of risk effects. The input mix in this case led to both increases and decreases in input use, which on net led to near zero changes in harvest. There is a slight skew towards increased harvest, but drastically less than the Coastal Groundfish fishery.

Groundfish trawlers consistently see small decreases of 2% in harvest (Figure 7). Capital was the primary driver of harvest reduction. However, it has a relatively low marginal productivity. Insurance decreases trawler capital use by about 8%, but the low productivity leads to only a 2% decrease in overall harvest.

Applying an insurance contract indemnified on θ instead of ω shifts the direction towards more overfishing (Figure 8). Prominent shifts occur in all fleets. For example, in Figure 7, the percent change in harvest for Coastal Seiners is indistinguishable from zero. With a θ index contract, Coastal Seiners would increase harvest by 18% (Figure 8).

Despite the risk decreasing dominance of capital in groundfish trawlers, fishers will choose to increase production as insurance protects against the added harvest risk. This result most

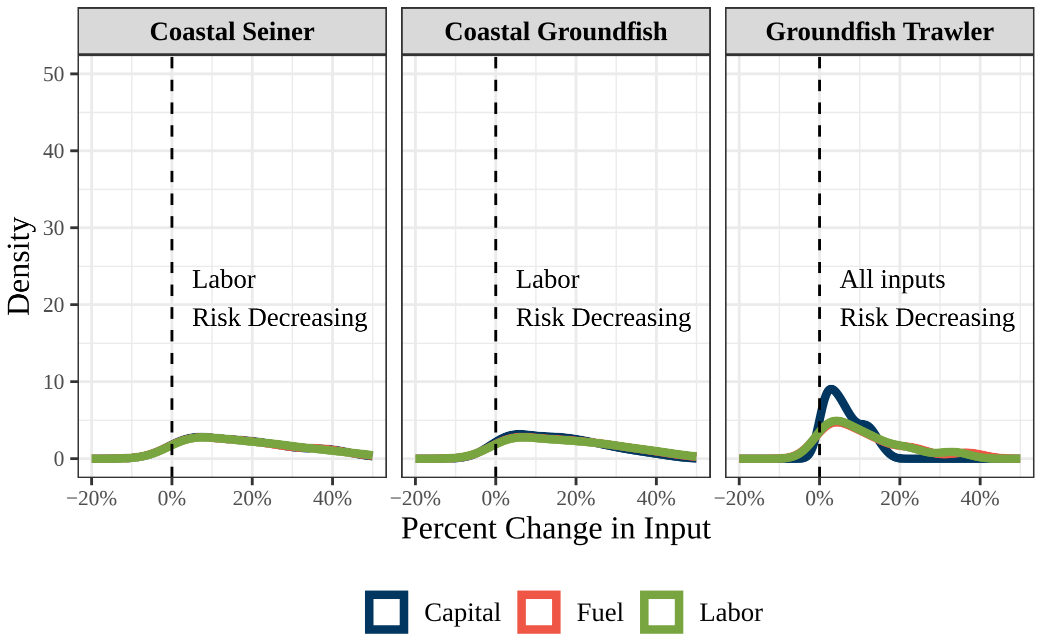

Figure 6: Density plots of the percent change in input use for each vessel type in Norwegian fisheries with insurance contracts built on stock risk θ. The dashed black line represents no change in input use. Risk decreasing inputs are labeled.

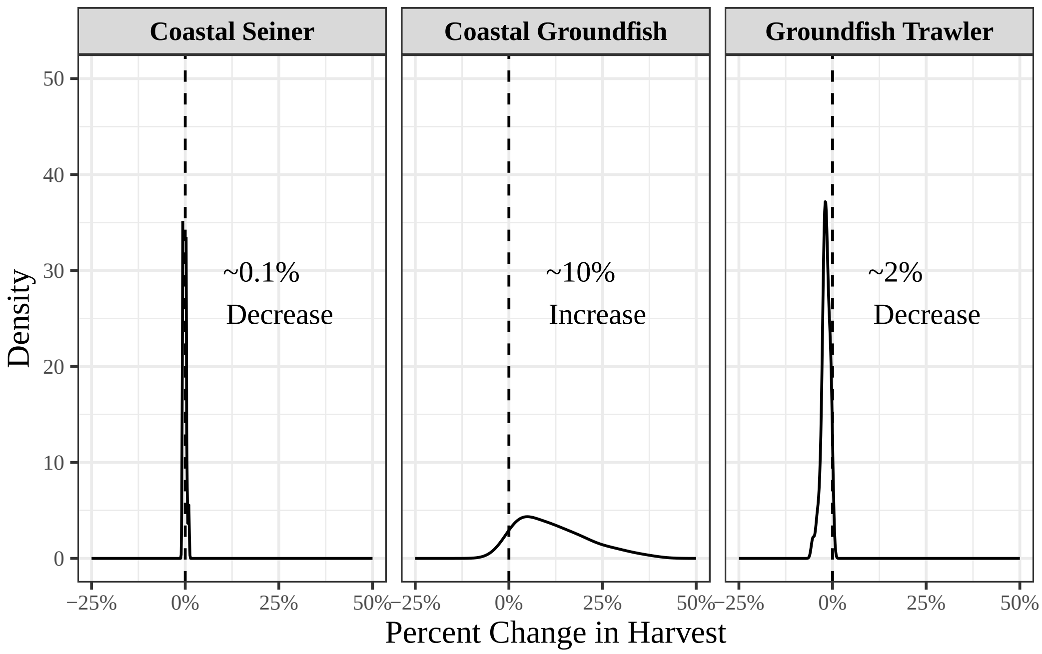

Figure 7: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries from an insurance contract trigged on extraction risks ω. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

clearly shows the impact of different insurance contracts and the potential for maladaptive behavior change. Without considering all the margins for change, insurance protecting against biological risk will encourage overfishing without additional constraints.

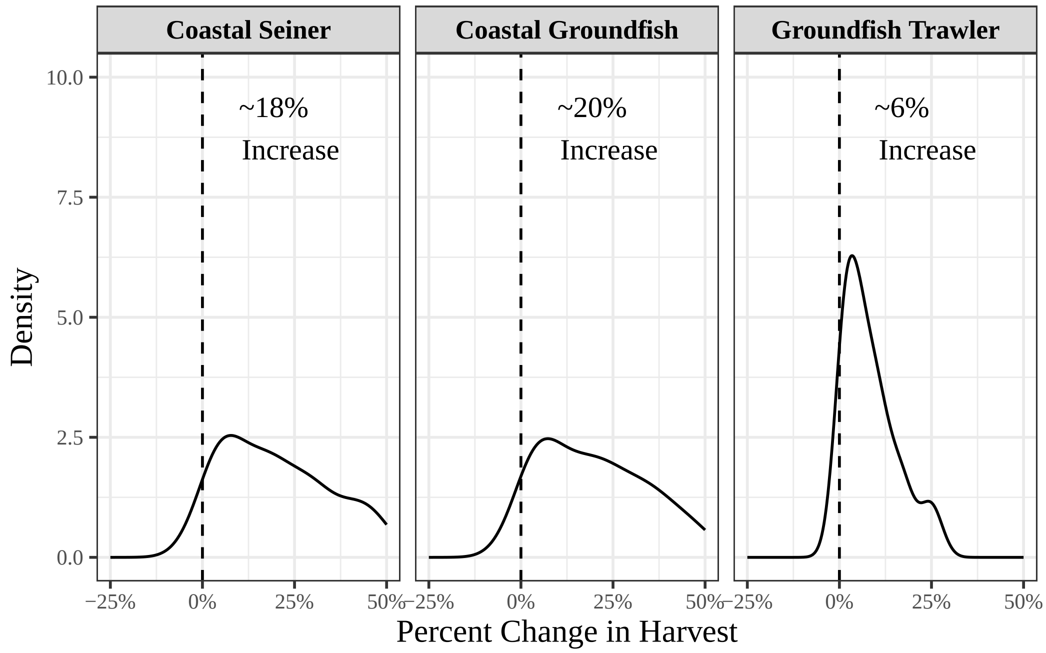

Figure 8: Density plots of the percent change in harvest for each vessel type in Norwegian fisheries with insurance contract indemnified on biological risk θ. The dashed line represents no change in harvest. The text labels represent the median percent change in harvest for each vessel type.

6 Discussion

This paper makes four distinct contributions. First, if fishery production is specified to traditional fishery models, then index insurance will lead to overfishing. Second, contract specification influences fisher behavior. Contracts that use stock risk as the index will always lead to increases, while contracts that use extraction shocks as the index could increase or decrease. The risk effects are the key drivers of this result similar to prior findings in agriculture. Third, risk effects can be overridden if there are multiple inputs, but conditions to maintain expected effects are possible. The overall effect of index insurance on harvest requires the total effect of all input changes. Fourth, insurance incentives that increase harvest lead to larger absolute changes than decreases in harvest.

The fundamental driver of fishers' behavior changes is whether the marginal change in productivity is balanced by the marginal change in risk. Fishers are more willing to increase production if insurance negates the additional risk of expanded production. Since insurance lowers risk, fishers need less self insurance through risk reducing inputs and can reduce their overall input use. However, using less inputs implies less catch and revenue creating a unique tension for risk decreasing inputs. Across all simulations, decreased input use was smaller than increased input use holding all other parameters constant. This is a clear demonstration of the tradeoff fishers face when considering risk decreasing input choices with insurance. Behavior change in fisheries will lean towards expanding production creating a dilemma for conservation efforts.

Index insurance would improve welfare in Norwegian fisheries, but also lead to changes in harvest that depends on the extraction risk effects of fishing fleets. The average utility gain was small for all simulations at 2% on average[7], but always positive indicating index insurance would be welfare improving. Therefore, insurance can provide immediate benefit to fishers, but the policymaker must take measures to mitigate the preserve incentive to expand fishing production. Otherwise, the long term health of the stock could be degraded and fishers would be worse off in the long run (Müller *et al.* 2017; John *et al.* 2019; Bulte and Haagsma 2021).

Norwegian pelagic groundfish trawlers would have the opposite considerations. When offered insurance they reduced their harvest by 2%. Though small, it will lead to improved fishery sustainability. The long term benefit of insurance would increase with improved stock health. The decline in harvest was driven by a reduction in overcapitalization, because capital was a significant risk decreasing input. Policymakers should attempt to identify fisheries with risk decreasing inputs for insurance contracts to improve sustainability if index insurance is to operate in isolation of other policies.

Ex-ante identification of input risk effects is challenging. Extraction risk effects remain an elusive concept in fisheries, and need to be estimated in order to articulate more accurate behavior changes of fishery index insurance. Crop covers and pesticide provide clear examples of risk decreasing inputs in agriculture, but what do risk decreasing inputs look like in fisheries? Labor is perhaps the more intuitive risk decreasing input. Technical expertise of crew and captains can hedge against luck when fishing (Alvarez *et al.* 2006). Better trained crew can deploy gear in a safe and timely manner, increasing the likelihood of effective sets.

Fuel as a risk increasing input in fisheries makes intuitive sense as well. Fuel is used to power vessels and is a direct cost of fishing. Fishers explore productive fishing grounds for the best location. Every hour at sea increases the harvest reward, but also the chances of failure.

Capital is a more complex input, because it is shown to be both risk increasing and decreasing. Capital in fisheries typically refer to vessel tonnage, engine power, and gear technology. Asche *et al.* (2020) noted that the trawler fishery, $\beta_k = -2.7$, was primarily an ocean going fleet that could move to the fish and handle adverse weather more readily. Quota allocations in the coastal fisheries are determined by vessel size with smaller vessels receiving proportionally

[7] The utility gains are smaller by construction as we manually introduce basis risk with an imperfect insurance contract that cannot simultaneously protect both risks.

more quota. Increasing vessel size would increase risk by introducing more variable quotas. The context of the fishery likely determines the risk effects of capital.

Capital acting as a risk decreasing input may explain overcapitalization in many fisheries around the world. In standard common pool resource models, adding risk aversion ought to lower aggregate effort (Mesterton-Gibbons 1993; Tilman *et al.* 2018). Yet, overcapitalization and overfishing are more often observed in the real world. Either fishers are never risk averse or the risk effects of capital are not as simple as the standard model suggests. When capital is allowed to be risk decreasing, optimal capital choices are much higher than without risk. Thus, fishers can still make rational, risk averse decisions even while overfishing.

Fishers exposure to multiple sources of risk further necessitates insurance, but also makes it more challenging to design. Proposition 3.1 and Proposition 3.2 shows the effects of insurance contract specifications on harvest. However, the leading candidates for possible indices in fisheries index insurance are currently weather variables most often associated with biological stock risks (Watson *et al.* 2023). Designing contracts solely on these variables may lead to harvest increases that run contrary to conservation goals.

Most bioeconomic models simplify the complex effects of stock dynamics into multiplicative or additive forms as modeled in this paper. Instead, different forms of risk could be embedded into the biological component of fishery models. Stock variance could be greater in overfished stocks instead of healthier ones, reflecting more vulnerability in weaker states (Sims *et al.* 2018). Adapting alternative, more biologically focused specifications of stock risk could change the behavioral effects of insurance. Fishers may be more willing to expose themselves to greater risk at more vulnerable stock levels with insurance. Alternatively, insurance could help mitigate risk and incentivize fishers to move toward healthier stocks with less variance by alleviating income pressures to fish. Further analysis is required to understand the full implications of stock risk effects in fisheries.

The transfer between inputs and insurance reflects the substitution between self-insurance and formal insurance (Quaas and Baumgärtner 2008). If index insurance is designed to reduce fishing capacity, efforts must be made to ensure that it does not take away from the self insurance capacity of fishers. Labor appears to be consistently risk reducing and acts as a form of self insurance. If index insurance incentivizes captains to hire less crew, the stock of fish may be preserved, but less employment may reverberate throughout the community. Fishing is often a primary employment opportunity in coastal communities. The resiliency of the community would be compromised rather than enhanced with fewer jobs. Contract stipulations could mandate that only cost expenses are covered by payouts thereby including lost wages to the crew. Agriculture contracts often are designed to directly cover expenses (He *et al.* 2020).

The primary form of risk mitigation in fisheries is management. To this point our analysis explicitly modeled scenarios without the existence of management. We wanted to analyze the interaction of insurance on fisher behavior in unconstrained settings first to derive a clearer incentive structure. Most fisheries are managed in some form. The interaction between management and insurance may be complementary or substitutes. For example, well managed fisheries that have responsive harvest control rules may not need insurance. The management system is already providing the necessary risk protection. Insurance demand and uptake may be low in these fisheries.

Insurance could instead complement management to provide the financial relief that management cannot offer. Managers often focus on the biological health of the fishery that can run at odds with fishers' desires to enhance their income. Insurance can act as the financial relief and allow managers to pursue more active strategies to protect fish stocks without political resistance from lowered quotas. Additionally, management can provide the constraints on insurance moral hazard so the income smoothing benefits are passed to fishers, but not the long term degradation. The interaction between insurance and management requires further investigation especially with the numerous management strategies that exist in fisheries.

Our model only directly models behavior change through moral hazards. Index insurance could be designed to incentivize other forms of sustainable behavior change. We define three pathways insurance can change behavior: Moral hazards, Quid Pro Quo, and Collective Action. Moral hazards were proven in this paper to have ambiguous impacts controlled by the risk characteristics of fishery inputs. The incentives of moral hazards will always exist, therefore other measures could be taken to either limit the downside behavioral effects of insurance or stimulate other forms of sustainable behavior.

Quid Pro Quo expands contract design to explicitly build in conservation measures. Fishers would be required to adopt sustainable practices in order to qualify for insurance. Quid Pro Quo is already used in agricultural insurance in the form of Good Farm Practices. Farmers must submit management plans to US Risk Management Agency that clearly outline their conservation practices in order to qualify for insurance. Working closely with management agencies, insurance companies could design contracts that require fishers to follow fishery specific management practices. For example, fishers may be incentivized to use more sustainable gear types, have an observer onboard, or reduce bycatch. A stipulation in in the COAST program is fishers must register their vessels with the participating countries fisheries department (Sainsbury *et al.* 2019). This requirement has brought greater data clarity to small scale Caribbean fisheries.

Further research would need to uncover the full impact of Quid Pro Quo, but an initial hypothesis would be fishers will be willing to adopt sustainable practices so long as the marginal gain in utility from the insurance is greater or equal to the marginal costs of the stipulated sustainable changes. Otherwise fishers will not want to buy the contracts and the insurance has no binding constraints to change the fishery.

Collective action ties insurance premiums to biological outcomes to leverage the political economy of the fishery. Insures could reduce premiums in fisheries that have robust management practices such as adaptive harvest control rules, stock assessments, or marine protected areas in the vicinity. Fishers could either pressure regulators to adopt these actions or form industry groups to undertake the required actions. Insurers would agree to this if triggers are connected to biological health so that negative shocks are less frequent and thus payouts occur less. Fishers gain from the reduced insurance premium and the increased sustainability of harvest with rigorous management in place.

Ultimately, if index insurance is to be used in fisheries, it must be designed with clear objectives and intentions. Index insurance can meet objectives of income stability and risk reduction, but there has been an implicit assumption by practitioners that index insurance will always lead to improved sustainability. Our results directly contradict that claim with the use of traditional models. Without considering the behavior change of fishers when adopting insurance, the outcomes may not be as expected. New insights derived from this paper will help guide the efficient and sustainable implementation of fisheries index insurance.

A Appendix

A.1 Proof of Lemma 2.1

Lemma 2.1 *Index insurance contracts built on θ will always lead to higher expected marginal profits in the good state*

$\frac{\mathbb{E}[\partial\pi|\theta<\bar{\theta}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\theta>\bar{\theta}]}{\partial x} < 0$

Proof. With standard fishery production, $\pi = f(x)(\hat{\beta}+\theta) - c(x)$, the first order conditions lead to optimal input choices that are equal across states of the world. Therefore $f(x^*)$, and $c(x^*)$ are equal across states. Where x^* denotes the optimal input choice.

$$\begin{aligned}\frac{\partial\mathbb{E}[\pi|\theta<\bar{\theta}]}{\partial x_m^*} - \frac{\partial\mathbb{E}[\pi|\theta>\bar{\theta}]}{\partial x_m^*} =& \cancel{f_{x^*}(x^*)\widehat{B}} + \mathbb{E}[\theta f_x(x^*)|\theta<\bar{\theta}] - \cancel{c_{x_m^*}(x^*)} \\ &- \cancel{f_{x^*}(x^*)\widehat{B}} - \mathbb{E}[\theta f_x(x^*)|\theta>\bar{\theta}] + \cancel{c_{x_m^*}(x^*)} \\ =& \mathbb{E}[\theta f_x(x^*)|\theta<\bar{\theta}] - \mathbb{E}[\theta f_x(x^*)|\theta>\bar{\theta}]\end{aligned} \tag{23}$$

With risky production profits are $\pi = \omega h(x) + f(x)(\hat{\beta}+\theta) - c(x)$. Independent shocks lead $\mathbb{E}[\omega|\theta \lesseqgtr \bar{\theta}] = 0$.

$$\begin{aligned}\frac{\partial\mathbb{E}[\pi|\theta<\bar{\theta}]}{\partial x_m^*} - \frac{\partial\mathbb{E}[\pi|\theta>\bar{\theta}]}{\partial x_m^*} =& \cancel{\mathbb{E}[\omega h_{x^*}(x^*)|\theta<\bar{\theta}]} + \cancel{f_{x^*}(x^*)\widehat{B}} + \mathbb{E}[\theta f_x(x^*)|\theta<\bar{\theta}] - \cancel{c_{x_m^*}(x^*)} \\ &- \cancel{\mathbb{E}[\omega h_{x^*}(x^*)|\theta>\bar{\theta}]} - \cancel{f_{x^*}(x^*)\widehat{B}} - \mathbb{E}[\theta f_x(x^*)|\theta>\bar{\theta}] + \cancel{c_{x_m^*}(x^*)} \\ =& \mathbb{E}[\theta f_x(x^*)|\theta<\bar{\theta}] - \mathbb{E}[\theta f_x(x^*)|\theta>\bar{\theta}]\end{aligned} \tag{24}$$

The concavity of $f(x)$ leads to $f_x(x) > 0$ always. Equation 23 and Equation 24 can then be signed to always be negative so that marginal profit in the good state is always higher when insurance contracts are triggered on θ.

$$\frac{\partial\mathbb{E}[\pi|\theta<\bar{\theta}]}{\partial x_m^*} - \frac{\partial\mathbb{E}[\pi|\theta>\bar{\theta}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\theta f_{x^*}(x^*)|\theta<\bar{\theta}] - \mathbb{E}[\theta f_{x^*}(x^*)|\theta>\bar{\theta}]}^{-}$$

□

A.2 Proof of Lemma 3.1

Lemma 3.1 *Expected marginal profit is higher in bad states for risk decreasing inputs when contracts are built on extraction risk* ω

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x} > 0$ *if* $h_x(x) < 0$.

Otherwise, risk increasing inputs lead to higher expected marginal profit in the good states.

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x} < 0$ *if* $h_x(x) > 0$

Proof. By the first order conditions, there exist optimal values of any individual input x that must be chosen before the realization of the states of the world. Therefore $h(x^*)$, $f(x^*)$, and $c(x^*)$ are equal across states. Where x^* denotes the optimal input choice.

Marginal utility in both states of the world is controlled by risk effects and the sign of the random variables. Given θ is independent of ω, the expected value of $\mathbb{E}[\theta|\omega \lesseqgtr \bar{\omega}] = 0$. The difference in expected marginal profit across insurance states is defined as:

$$\begin{aligned}\frac{\partial\mathbb{E}[\pi|\omega<\bar{\omega}]}{\partial x_m^*} - \frac{\partial\mathbb{E}[\pi|\omega>\bar{\omega}]}{\partial x_m^*} =& \mathbb{E}[\omega h_{x^*}(x^*)|\omega<\bar{\omega}] + \cancel{f_{x^*}(x^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(x^*)|\omega<\bar{\omega}]} - \cancel{c_{x_m^*}(x^*)} \\ & - \mathbb{E}[\omega h_{x^*}(x^*)|\omega>\bar{\omega}] + \cancel{f_{x^*}(x^*)\widehat{B}} + \cancel{\mathbb{E}[\theta f_x(x^*)|\omega>\bar{\omega}]} - \cancel{c_{x_m^*}(x^*)} \\ =& \mathbb{E}[\omega h_{x^*}(x^*)|\omega<\bar{\omega}] - \mathbb{E}[\omega h_{x^*}(x^*)|\omega>\bar{\omega}]\end{aligned} \tag{25}$$

If an input is risk decreasing then $h_x(x) < 0$. Then Equation 25 is positive and marginal profit in the bad state is greater than the marginal profit in the good state. Adding more of a risk reducing input reduces the negative impact in the bad state relative to the good state.

$$\frac{\partial\mathbb{E}[\pi|\omega<\bar{\omega}]}{\partial x^*} - \frac{\partial\mathbb{E}[\pi|\omega>\bar{\omega}]}{\partial x^*} = \overbrace{\mathbb{E}[\omega h_{x^*}(x^*)|\omega<\bar{\omega}] - \mathbb{E}[\omega h_{x^*}(x^*)|\omega>\bar{\omega}]}^{+}$$

Repeating the same steps for risk increasing inputs $h_x(x) > 0$ shows that marginal profit in the bad state is less than marginal profit in the good state.

$$\frac{\partial\mathbb{E}[\pi|\omega<\bar{\omega}]}{\partial x_m^*} - \frac{\partial\mathbb{E}[\pi|\omega>\bar{\omega}]}{\partial x_m^*} = \overbrace{\mathbb{E}[\omega h_{x^*}(x^*)|\omega<\bar{\omega}] - \mathbb{E}[\omega h_{x^*}(x^*)|\omega>\bar{\omega}]}^{-}$$

□

A.3 Proof of Proposition 4.1

Proposition 4.1 *In fisheries with two inputs, index insurance specified with contracts on* ω *will increase (decrease) the optimal use of a specific input if the input's risk effects are increasing (decreasing) when the following sufficient condition is true:*

$\frac{\partial U}{\partial x_a x_b} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial U}{\partial x_a \partial x_b} < 0$ *when inputs have opposite risk effects.*

Otherwise, index insurance will have ambiguous effects on optimal input choice.

Proof. We use the same insurance design from Section 3. Fishers now maximize expected utility by selecting two inputs. Contracts are built on ω.

$$\begin{aligned} U \equiv \max_{x_a, x_b} \mathbb{E}[U] = \int_{-\infty}^{\infty} \Bigg[& \int_{-\infty}^{\bar{\omega}} j(\omega, \theta) u(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) d\omega \\ & + \int_{\bar{\omega}}^{\infty} j(\omega, \theta) u(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) d\omega \Bigg] d\theta \end{aligned} \tag{26}$$

Taking the first order conditions yields:

$$\begin{aligned} \frac{\partial U}{\partial x_a} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega, \theta) u_{x_a}(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x_a}(X, \hat{B}, \theta, \omega) d\omega \\ &\quad + \int_{\bar{\omega}}^{\infty} j(\omega, \theta) u_{x_a}(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x_a}(X, \hat{B}, \theta, \omega) d\omega \Bigg] d\theta \\ &= 0 \\ \frac{\partial U}{\partial x_b} &= \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega, \theta) u_{x_b}(\pi(X, \hat{B}, \theta, \omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x_b}(X, \hat{B}, \theta, \omega) d\omega \\ &\quad + \int_{\bar{\omega}}^{\infty} j(\omega, \theta) u_{x_b}(\pi(X, \hat{B}, \theta, \omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x_b}(X, \hat{B}, \theta, \omega) d\omega \Bigg] d\theta \\ &= 0 \end{aligned} \tag{27}$$

Assuming the first order condition is satisfied, we can use the implicit function theorem (IFT) to look at the impact of a change in the exogenous insurance contract. Applying IFT yields a system of equations that determine the impact of insurance on each optimal input:

$$\begin{aligned} \frac{\partial x_a}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{\partial U}{\partial x_b \partial x_b} \frac{\partial U}{\partial x_a \partial \gamma} - \frac{\partial U}{\partial x_a \partial x_b} \frac{\partial U}{\partial x_b \partial \gamma} \right] \\ \frac{\partial x_b}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{-\partial U}{\partial x_b \partial x_a} \frac{\partial U}{\partial x_a \partial \gamma} + \frac{\partial U}{\partial x_a \partial x_a} \frac{\partial U}{\partial x_b \partial \gamma} \right] \end{aligned} \tag{28}$$

Because the determinant (DET) will always be positive by the second-order condition, we can focus on the interior of the brackets. If positive, then insurance will lower use of that specific input and vice versa. The partial derivatives in Equation 28 are complex. Their complete derivations are included in Section A.4.

Lemma 3.1 allows us to sign the partial equations Equation 34 and Equation 35 for any risk effect on either input. Concave utility by definition leads to $u'' < 0$. For simplicity, we will only focus on $\frac{\partial U}{\partial x_a \partial \gamma}$, but all applies equally to $\frac{\partial U}{\partial x_b \partial \gamma}$. Insurance payouts equalize profits between different states. If insurance completely covers all loss and x_a is risk increasing, then $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive.

$$\begin{aligned}\frac{U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} & \overbrace{j_\theta(\theta) J(\bar{\theta})(1 - J(\bar{\theta}))u''(\theta, \cdot)}^{-} \\ & \left[\underbrace{\int_{-\infty}^{\bar{\omega}} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega - \int_{\bar{\theta}}^{\infty} j_\omega(\omega) \frac{\partial \pi}{\partial x_a} d\omega}_{-} \right] d\theta \\ > 0 & \end{aligned} \tag{29}$$

Suppose both inputs are risk increasing so $\frac{\partial U}{\partial x_a \partial \gamma}$ and $\frac{\partial U}{\partial x_b \partial \gamma}$ are positive. The only way for Equation 28 to be unambiguously positive is for $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_b \partial x_a}$ to be positive.

$$\frac{\partial x_a}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{+}}^{-} \right] > 0$$

Both risk increasing inputs will be raised with index insurance. Repeating the same steps above with risk decreasing inputs shows both inputs unambiguously decrease with index insurance.

Now suppose inputs have mixed risk effects. For simplicity, x_a will be risk increasing and x_b will be risk decreasing. The results will hold for the opposite case. By Lemma 3.1, $\frac{\partial U}{\partial x_a \partial \gamma}$ is positive, while $\frac{\partial U}{\partial x_b \partial \gamma}$ is negative. Equation 28 will be unambiguously positive if $\frac{\partial U}{\partial x_a \partial x_b}$ and $\frac{\partial U}{\partial x_b \partial x_a}$ are negative.

$$\frac{\partial x_a}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial U}{\partial x_b \partial x_b}}^{-} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} - \overbrace{\frac{\partial U}{\partial x_a \partial x_b}}^{+} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{-} \right] > 0$$

$$\frac{\partial x_b}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial U}{\partial x_b \partial x_a}}^{+} \overbrace{\frac{\partial U}{\partial x_a \partial \gamma}}^{+} + \overbrace{\frac{\partial U}{\partial x_a \partial x_a}}^{-} \overbrace{\frac{\partial U}{\partial x_b \partial \gamma}}^{-}}^{+} \right] < 0$$

The risk increasing input will be raised with index insurance, while the risk decreasing input will be lowered.

If these conditions do not hold, then it is impossible to determine which additive element outweighs the other, and the insurance effects on optimal input use will be ambiguous regardless of the underlying risk effects of an input. □

A.4 Partial derivatives

Partial derivatives used to sign Equation 28 are shown below. For brevity, $\pi(X, \hat{B}, \omega, \theta)$ is reduced to π.

$$\begin{aligned} \frac{\partial U}{\partial x_a \partial x_a} = \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a x_a}]d\omega \\ + \int_{\bar{\omega}}^{\infty} j(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a x_a}]d\omega \Bigg] \, d\theta \end{aligned} \tag{30}$$

$$\begin{aligned} \frac{\partial U}{\partial x_b \partial x_b} = \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b x_b}]d\omega \\ \int_{\bar{\omega}}^{\infty} j(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b x_b}]d\omega \Bigg] \, d\theta \end{aligned} \tag{31}$$

$$\begin{aligned} \frac{\partial U}{\partial x_a \partial x_b} = \int_{-\infty}^{\infty} \Bigg[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a x_b}]d\omega \\ \int_{\bar{\omega}}^{\infty} j(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a x_b}]d\omega \Bigg] \, d\theta \end{aligned} \tag{32}$$

$$\frac{\partial U}{\partial x_b \partial x_a} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)[u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b x_a}]d\omega \right.$$
$$\left. \int_{\bar{\omega}}^{\infty} j(\omega,\theta)[u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}\frac{\partial \pi}{\partial x_b} + u'(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b x_a}]d\omega \right] d\theta \tag{33}$$

$$\frac{\partial U}{\partial x_a \partial \gamma} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_a}(1-J(\bar{\omega})d\omega \right.$$
$$\left. \int_{\bar{\omega}}^{\infty} j(\omega,\theta)u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_a}(-J(\bar{\omega}))d\omega \right] d\theta \tag{34}$$

$$\frac{\partial U}{\partial x_b \partial \gamma} = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\bar{\omega}} j(\omega,\theta)u''(\pi + (1-J(\bar{\omega}))\gamma)\frac{\partial \pi}{\partial x_b}(1-J(\bar{\omega})d\omega \right.$$
$$\left. \int_{\bar{\omega}}^{\infty} j(\omega,\theta)u''(\pi - J(\bar{\omega})\gamma)\frac{\partial \pi}{\partial x_b}(-J(\bar{\omega}))d\omega \right] d\theta \tag{35}$$

A.5 Correlation Proofs

Lemma A.1. *When shocks are perfectly correlated, expected marginal profit is always higher in the good state when an input, x_m, is risk increasing and ambiguous when x_m is risk decreasing. This hold regardless of the chosen index.*

$\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} < 0$ *if* $h_{x_m}(X) > 0$

And, $\frac{\mathbb{E}[\partial\pi|\omega<\bar{\omega}]}{\partial x_m} - \frac{\mathbb{E}[\partial\pi|\omega>\bar{\omega}]}{\partial x_m} \lesseqgtr 0$ *if* $h_{x_m}(X) < 0$.

Proof. Perfect correlation between two random variables centered at 0 imply that whenever one variable is negative, so too is the other. Due to this, we focus only on ω as the index. The proof follows identically if replaced by an index on θ.

$$\frac{\partial\mathbb{E}[\pi|\omega<\bar{\omega}]}{\partial x} - \frac{\partial\mathbb{E}[\pi|\omega>\bar{\omega}]}{\partial x} = \cancel{f_x(x)}\hat{B} + \mathbb{E}[\theta f_x(x)|\omega<\bar{\omega}] + \mathbb{E}[\omega h_x(x)|\omega<\bar{\omega}] - \cancel{c}(x)$$
$$-\cancel{f_x(x)}\hat{B} + \mathbb{E}[\theta f_x(x)|\omega>\bar{\omega}] + \mathbb{E}[\omega h_x(x)|\omega>\bar{\omega}] - \cancel{c}(x) \tag{36}$$

When $h_x(X) > 0$, Equation 36 is always negative. Expected marginal profit is always higher in the good trigger state when shocks are perfectly correlated.

When $h_x(X) < 0$, Equation 36 is ambiguous. The sign of each line depends on the relative effect between $f_x(X)$ and $h_x(X)$. If the risk effects term dominates then Equation 36 will be positive. Without further information it is impossible to know which effect dominates. □

Proposition A.1. *For feasible index insurance contracts specified at either trigger, $\bar{\omega} = 0$ or $\bar{\theta} = 0$, when ω and θ are perfectly correlated random variables, the change in the optimal input is ambiguous when $h_x(x) < 0$ and increases when $h_x(x) > 0$.*

Proof. Perfect correlation implies $\theta < 0$ when $\omega < 0$ and $\theta > 0$ when $\omega > 0$ since both distributions have mean zero, $\mathbb{E}[\theta] \equiv \mathbb{E}[\omega] = 0$. The bounds of the integral can be with respect to either trigger. For simplicity, we will use $\bar{\omega}$ as the trigger, but the proof holds with $\bar{\theta}$.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = & \int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) + (1 - J(\bar{\omega}))\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(1 - J(\bar{\omega})) d\omega d\theta \\ & + \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j(\omega,\theta) u''(\pi(x,\hat{B},\theta,\omega) - J(\bar{\omega})\gamma) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega)(-J(\bar{\omega})) d\omega d\theta\end{aligned} \tag{37}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 37.

$$\begin{aligned}\frac{U}{\partial x \partial \gamma} = & u''(\cdot) J(\bar{\omega})(1 - J(\bar{\omega})) \\ & \times \left[\int_{-\infty}^{\bar{\omega}} \int_{-\infty}^{\bar{\omega}} j(\omega,\theta) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta - \int_{\bar{\omega}}^{\infty} \int_{\bar{\omega}}^{\infty} j(\omega,\theta) \frac{\partial \pi}{\partial x}(x,\hat{B},\theta,\omega) d\omega d\theta \right]\end{aligned} \tag{38}$$

By Lemma A.1, when $h_x(X) < 0$ the interior is ambiguous so Equation 38 cannot be signed, but is unambiguously positive when $h_x(X) > 0$. □

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